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A comparative life cycle assessment of dental restorative materials

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ABSTRACT

Objectives: Different types of direct-placement dental materials are used for the restoration of structure, function and aesthetics of teeth. The aim of this research investigation is to determine, through a comparative cradle-to-gate life cycle assessment, the environmental impacts of three direct-placement dental restorative materials (DRMs) and their associated packaging.

Methods: Three direct-placement dental materials; dental amalgam, resin-based composite (RBC) and glass polyalkenoate cements (GIC) are assessed using primary data from a manufacturer (SDI Limited, Australia). The functional unit consisted of 'one dental restoration' of each restorative system under investigation: 1.14 g of dental amalgam; 0.25 g of RBC (plus the adhesive = 0.10 g); and 0.54 g of GIC. The system boundary per restoration included the raw materials and their associated packaging materials for each DRM together with the processing steps for both the materials and packaging. The environmental impacts were assessed using an Egalitarian approach under the ReCiPe method using Umberto software and the Ecoinvent database. Nine different impact categories were used to compare the environmental performance of these materials.

Results: Dental amalgam had the highest impact across most of the categories, but RBC had the highest Global Warming Potential. The highest sources of the environmental impacts for each restorative material were: Amalgam, derived from material use; RBC, derived from energy use in processing material and packaging material; GIC, derived from material and energy use for packaging.

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Significance: Less intensive energy sources or more sustainable packaging materials can potentially reduce the impacts associated with RBC and GIC thus making them suitable alternatives to dental amalgam.

1. Introduction

The most commonly utilised direct-placement dental restorative materials are dental amalgam, resin-based composite (RBC) and glass polyalkenoate cements (better known as glass ionomer cements or GICs) [1]. Dental amalgam is an alloy of mercury (~50% wt), silver (~30% wt), copper (~13% wt), tin (~8% wt), zinc (~8% wt) and other trace elements. It has been used as a dental restorative material for over 150 years [2]. Since this time, the presence of mercury in dental amalgam has been contentious, initially over health concerns to the patient. The current position of the Scientific Committee on Emerging and Newly Identified Health Risks (SCENIHR) states that dental amalgam is safe and well tested clinically [3]. More recently the environmental pollutant effect of dental amalgam has gained greater notoriety due to its release into the environment during the material's life cycle [4,5]. In 2010 an estimated 270–341 metric tonnes of mercury globally was derived from the use of dental amalgam, accounting for 20% of global mercury consumption [6]. The Minamata Convention on Mercury, which has advised a phase-down in the use of dental amalgam, has further accelerated a shift towards the use of alternative materials, including RBC and GIC-based materials [7]. Despite the advised phase-down of dental amalgam as a DRM, following the ratification of the Minamata treaty, it remains the DRM of choice in some low- and middle-income countries due to its relatively low cost and effectiveness [8].

RBC consists of an inorganic glass filler phase coupled to, and contained within, an organic resin-based polymer matrix phase. The main constituents of the plastic resin matrix are typically methacrylate-based. Other components key to controlling the polymerisation reaction of this material include initiators, accelerators, inhibitors and photo-stabilisers [9]. Over 500 million RBC restorations were estimated to have been placed worldwide in 2012 and current usage is expected to be higher due to increased overall applications in the last decade [1]. RBC restorations have a greater range of applications than dental amalgam as they are adhesive to tooth structure, restore the structural integrity of the teeth, are tooth-coloured and have clinically acceptable levels of mechanical performance, degradation resistance, and durability [10,11]. These restorations are not reported to pose any form of health hazard with some emerging data on their environmental impact that is considered to be low [12–14].

GIC materials consist of fluoro-alumino-silicate glass that, when combined with an organic polyacid, triggers an acid-base setting reaction. The resulting tooth-coloured restorations have specific adhesion to the inorganic constituents of teeth and are commonly used in non-stress bearing dental applications and paediatric dentistry; principally due to reported cariostatic properties brought about through dynamic release of fluoride into the immediate surrounding tooth structure. These cements are commonly available as a pure GIC or combined with a methacrylate polymer resin (resin-modified GICs or RMGICs) in an attempt to combine the optimal properties of both GIC and RBC [9].

Dental amalgam, RBC and GIC-based materials can be contained in single-use sealed rigid plastic containers, described as compules or spills (dental amalgam), or in bulk packaging for multiple uses. This packaging facilitates transportation, predictable mixing, ease of use and delivery into the tooth, protection from ambient light or moisture and extending the product shelf-life. In addition, these containers are further transported in secondary and/or tertiary packaging. These delivery containers are designed for single use applications and are disposed of, along with associated packaging, into clinical or municipal waste streams. The material containers and their associated packaging are made up of heteropolymers that are assembled as a complex compound structure and are therefore difficult to recycle. There may also be residual unused material present in the containers which is also disposed into the aforementioned waste streams.

Despite the clear positive benefits of these materials to global public health [15], to date few studies have been performed to understand their impact on the environment. Life cycle assessments (LCA) [16] provide a robust methodology to determine the environmental impact of a material, product or service [17]. The methodology is supported by BS EN ISO 14040:2006 [17] which provides guidance relating to the four steps necessary to complete a LCA. Within oral healthcare, LCA is increasingly being used to assess environmental impacts. LCAs have been applied to measure the environmental impact of dental equipment and sundries, clinical procedures and oral hygiene devices. Unger and Landis (2014) performed a comparative LCA of reused versus disposable dental burs highlighting the necessity of increasing operational efficiency to reduce environmental impact [18]. Munhoz et al. (2013) developed a streamlined life cycle inventory (LCI) of the dental local anaesthetic compule syringe [19]. Their results highlighted the impact of LCA by providing solutions to reduce the energy use by 20% and solid waste production by 40% during manufacturing.

LCA to determine the environmental impact of clinical procedures include the study by Borglin et al.(2021), that focused on the dental examination procedure and identified a number of major contributors or hotspots that could be addressed [20]. Duane et al. (2020) applied LCA to endodontic procedures, identifying 4.9 kg CO_2-eq [21]. LCA methodology has also been used to compare the sustainability of different types of toothbrushes [22,23] highlighting that the use of recycled plastic in the manufacturing process leads to a reduction in the carbon footprint (kg CO_2-eq) and disability-adjusted life years (DALYs) compared to other potential manufacturing materials.

The first instance of carbon accounting applied to dental materials is in a Public Health England (PHE) report commissioned by the Centre for Sustainable Healthcare (2018), that assessed the carbon emissions associated with seventeen key dental procedures [24]. This study included the impact of restorations using dental amalgam, RBC and GIC dental materials. The system boundary applied to this research included patient travel, staff travel, procurement, energy, water, waste, and nitrous oxide; the impact relating to capital items was excluded. The results found that a dental amalgam restoration has a carbon footprint of 14.8 kg CO2-eq, compared to 14.75 kg CO2-eq for a composite filling, while a GIC filling has a carbon footprint of only 8.6 kg CO2-eq. This important PHE study identified the types of dental procedures that are responsible for large amounts of greenhouse gas emissions. Critically, however it did not consider the environmental impacts of the actual materials as used in the clinical setting. There is an imperative need to understand the environmental impacts associated with the manufacturing of direct-placement dental restorative materials and their associated packaging through a comprehensive and robust LCA.

Beyond the actual materials, the global impacts of plastics and especially single-use plastics (SUPs), for example as used for packaging for DRMs, are of increasing concern [25–27]. Unger et al. used LCA to determine if the use of biopolymers in the manufacture of medical devices as a substitute for commonly used plastics such as low-density polyethylene, polypropylene and neoprene, led to a reduction in environmental impact [28]. Their results showed that although there was a reduction in carcinogenic and non-carcinogenic impacts, respiratory effects and cumulate energy demand were observed.

The aim of this research investigation is to determine, through a comparative assessment, the environmental impacts of three direct-placement dental restorative materials (DRMs) and their associated packaging as a cradle-to-gate LCA i.e. from the extraction of natural resources (cradle) to the factory gate prior to distribution to the customer [29]. A new integrated framework is developed to guide future environmental impact assessments of materials that considers empirical inputs and packaging (Fig. 1).

The framework extends the basic elements from a classical LCA process which includes goal & scope definition, inventory analysis, impact assessment and interpretation, by embedding a closed loop system that covers externalities like LCA software and database, primary data source from manufacturer and redesign for impact reduction. The methodology of this investigation includes primary data from manufacturer for materials and packaging materials. This integrated framework positions the role of LCA as an iterative exercise with the results of an initial assessment used for product and/or process improvement. These improvements can be implemented and refined through further LCA so the process can be utilised to enable continuous improvements and understanding of environmental impacts.

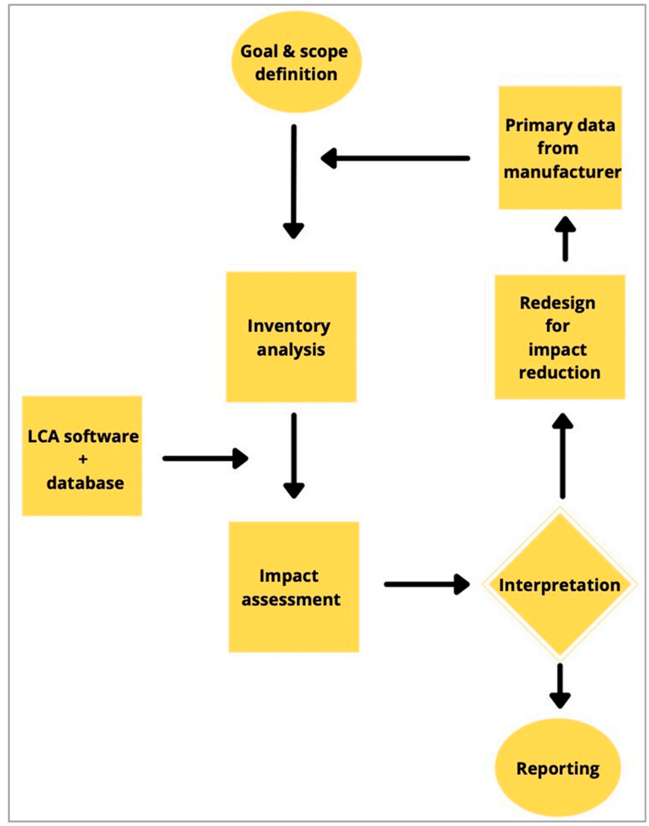

Fig. 1 – Life cycle assessment system framework for comparing dental restorative materials.

2. Materials and methods

The environmental impacts of the three main direct-placement dental restorative materials and their associated packaging are investigated: Dental amalgam, RBC (and its associated adhesive bonding agent) and GIC. Packaging was included to determine the environmental impact of packaging as a source of single-use plastic (SUP) within dentistry. A new integrated framework is developed to guide future environmental impact assessments of materials that considers empirical inputs and packaging (Fig. 1).

Comparative LCA of three direct-placement DRMs; dental amalgam, a RBC and a GIC, which are supported by empirical data from the materials' manufacturer (SDI Limited, Australia). BS EN ISO 14040:2006 outlines the four steps required to complete a robust and reliable LCA [17]. Step one, goal and scope definition (Section 2.1), establishes a system boundary within which all of the relevant processes relating to the chosen product or service are considered. The boundary depends on the chosen application, any necessary assumptions and the audience of the final output. The boundary may include the complete life cycle of the product, cradle-to-grave/cradle, or only certain steps in the production process and can be refined throughout the LCA. Step two (Section 2.2), inventory analysis, requires the data relating to the material and energy inputs and outputs to be collated and summated. During the life cycle impact assessment (LCIA), step three (Section 2.3), inputs and outputs are assigned to the chosen impact categories and transformed into environmental impacts for analysis. The results of the LCIA are then analysed in detail through step four, interpretation (Section 4) [17].

2.1. *Goal and scope definition*

The functional unit applied to this investigation, used to define the scope of the study [30], was 'one dental restoration' of each DRM system under investigation, according to the system boundary of this study (Fig. 2). This includes a) the impact of the raw materials, and their processing steps, required per restoration and b) the packaging materials, and their processing steps, required per restoration. The 'use phase' was omitted from this study as these impacts have already been established [24].

2.2. *Inventory analysis*

The material and energy inputs and outputs required for the LCI of each DRM system and associated packaging, in line with the system boundary in Fig. 2, were provided by a major international dental manufacturing company. The 3 DRMs investigated are representative of dental amalgam, RBC and GIC. The LCI data was collected directly by the Senior Research and Development Scientist for SDI Limited (Agrissais M) for this study and it is considered to be reliable, robust and of high quality. In line with the chosen functional unit, the mass of each DRM restoration was given as: RBC = 0.25 g (plus the RBC adhesive = 0.10 g); GIC = 0.54 g; amalgam = 1.14 g.

2.3. *Impact assessment*

This study used the ReCiPe Midpoint v1.13 impact assessment methodology using the Egalitarian I approach. This methodology translates resource extraction and emissions into environmental impacts using characterisation factors at both midpoint and endpoint level [31]. Midpoint level characterisation factors occur along the pathway of impact and endpoint level characterisation factors relate to the human health, resource scarcity and ecosystem quality areas of protection. Although the two levels of characterisation complement each other, the midpoint level relates strongly to environmental flows and has inherently low uncertainty associated with it and therefore was used for the environmental analysis in this research. The egalitarian approach was chosen when comparisons were made as it provides the most precautionary perspective, over the longest timeline and all impact pathways where data is available [31]. All impact assessments were carried out using Umberto software (iPoint-sytems gmbh, Reutlingen, Germany).

Where data was missing from the Ecoinvent database for individual inputs, published protocols were implemented based on chemical characteristics or functional parallels [32,33]. These parallels were further confirmed by the manufacturer of the materials used as being appropriate to the scope of the study.

The equation for the contributions of individual emissions within the system, is given in Eq. (1):

$$\text{Process} \quad LCA = \sum_{i=1}^{n} A_{p(i)} \times E_{p(i)} \tag{1}$$

Ap represents the inputs (*i*) into the supply chain, according to the system boundary shown in Fig. 2, this includes raw material extraction, energy use and production processes; *n* is the total number of inputs (*i*) and *Ep* is the

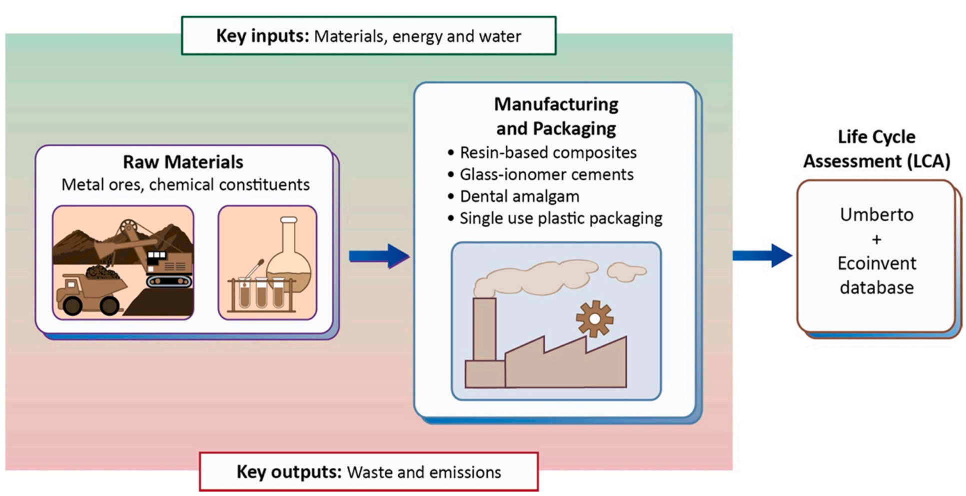

Fig. 2 – Life Cycle Assessment system boundary, depicting the materials and energy flows associated with the fabrication of RBCs, GICs, dental amalgam and the associated packaging requirements.

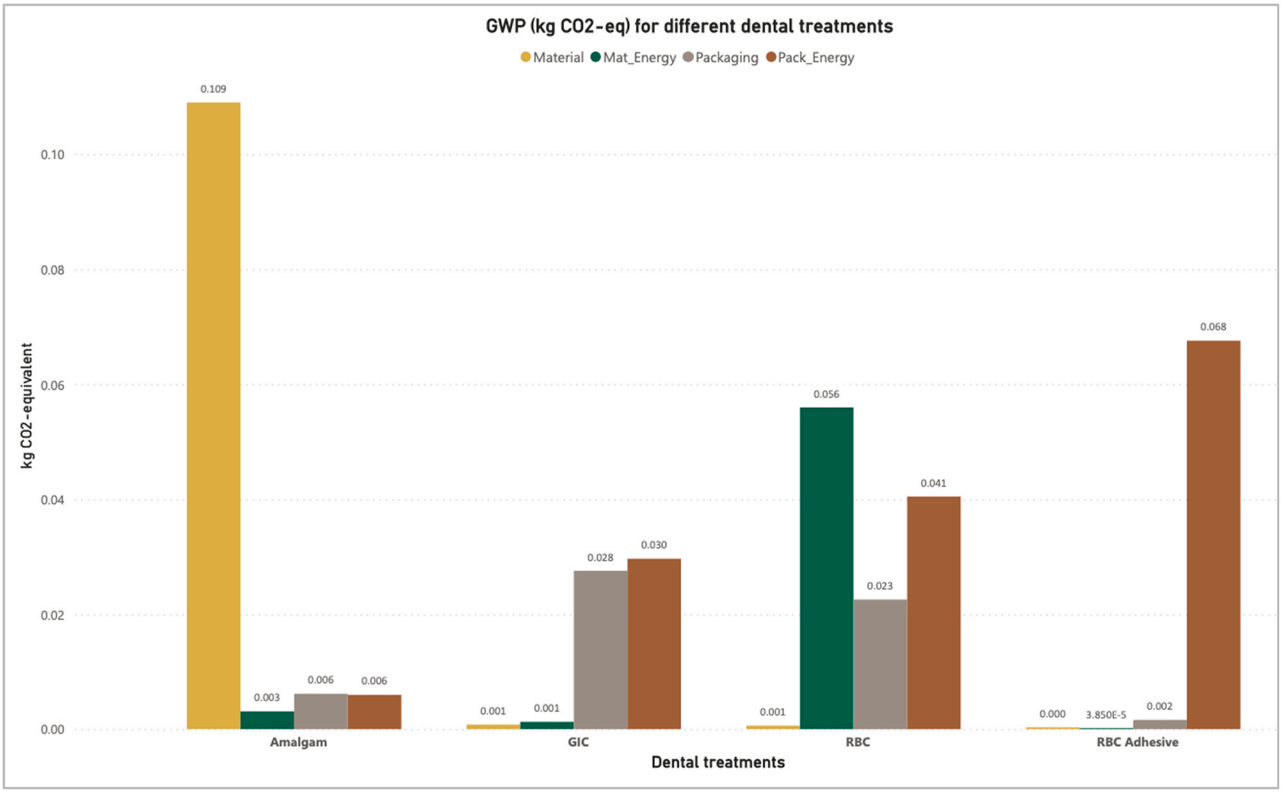

Fig. 3 – Comparison of GWP from different sources within different DRMs.

emissions intensity of the chosen impact categories outlined above, for each input (*i*) into the supply chain [33].

To determine the environmental impacts of the manufacturing processes used in the production of the DRMs and the associated packaging, Eqs. (2) and (3) were utilised to calculate the electrical energy and thermal energy requirements respectively.

$$E = P \cdot t \quad (2)$$

$$Q = C_p \cdot m \cdot \triangle T \quad (3)$$

In Eq. (2), E represents the electrical energy requirement (kWh), P corresponds to the equipment's power requirements (W) and time (s) is represented by t. With respect to Eq. (3), the thermal energy requirement is represented by Q, Cp denotes the specific heat capacity (J kg^{-1} K^{-1}) of the material being processes, the mass (kg) of the material being processed is represented by m and finally the change in temperature (K) during the manufacturing process is represented by ΔT [34].

3. Results

3.1. *Total life cycle impacts*

This section provides the results of the process LCAs for the three DRM systems analysed in this study, namely dental amalgam, RBC, RBC adhesive and GIC and all their associated packaging requirements (the LCIA results have been provided in the supplementary excel file). Fig. 3 displays the Global Warming Potential (GWP) as measured in kg CO_2-equivalents, associated with the DRMs. We focused on GWP as most of the existing LCA studies report results for GWP which can facilitate a direct comparison. Moreover, global warming potential is generally known to a wider audience than other indicators.

For illustrative purposes, the composite and adhesive elements within the RBC have been displayed separately. It can be seen that each had a different source dominating the contributions to overall GWP. For instance, Material can be seen as the largest GWP contributor for dental amalgam. For RBC, energy used in Material production was the highest contributing source for GWP. For the RBC adhesive and GIC, energy use in packaging had the highest GWP.

Overall, dental amalgam had the highest GWP (1.25E-01 kg CO_2-eq), followed by RBC (1.20E-01 kg CO_2-eq), RBC adhesive (6.96E-02 kg CO_2-eq) and GIC (5.94E-02 kg CO_2-eq). For a more holistic analysis, the impacts for RBC and adhesive should be summed up together. In such a case, RBC has the highest GWP at 1.89E-01 kg CO_2-eq.

It is pertinent to mention here that other life cycle impact categories may present a different picture of the results. This can be seen in Fig. 4 that presents the share of the different DRMs in a combined form for nine different LCIA categories. These categories include Global Warming Potential (GWP), Fresh Water Ecotoxicity (FETP), Freshwater Eutrophication (FEP), Human Toxicity (HTP), Marine Ecotoxicity (METP), Marine Eutrophication (MEP), Metal Depletion (MDP), Ozone

Depletion (OD), terrestrial Acidification (TAP), and Water Depletion (WDP). Once again, the results for RBC composite and adhesive have been presented separately for clarity and detail. The figure has been adjusted so that the y-axis starts at 30%.

Fig. 4 shows that dental amalgam has the highest relative impact across fifteen of the nine LCIA categories while RBC (composite + adhesive) has the highest impact for GWP and FDP. RBC has the highest impact for OD and the second-highest impact for ULOP. Thus, by focusing on only one or few LCIA categories the narrative of the analysis can change completely. As such, it is important to have a holistic environmental impact assessment with different categories presented for a complete picture.

3.2. *Individual life cycle impacts*

Figs. 5–7 present the environmental impacts of amalgam, RBC (including adhesive) and GIC respectively. These impacts are sub-divided into the Material, energy invested in material processing (Mat_energy), Packaging and the energy used in Processing the packaging (Pack_Energy).

The indicators are normalised to provide an absolute indicator of 100% for each value which highlights the percentage contribution of each component to the total impact. For clear visibility the figures show nine LCIA categories including GWP, FETP, FEP, HTP, METP, MEP, OD, TAP, and WDP.

The bar chart in Fig. 6 shows the relative contribution of sources in the overall environmental impacts of dental amalgam production. It can be seen that for dental amalgam, Material contributed the highest environmental impact (> 80%) across all of the LCIA categories. As such, the figure was adjusted so that the y-axis starts at 80%, to show the relative contributions of other sources clearly. The second largest contributor across most of the LCIA categories was Material Packaging. The impact of energy consumption for Packaging Processing was generally higher than that for energy used for Material Processing.

The bar for GWP has been highlighted in the chart and shows that Material had the highest share (87.61%) in the total GWP. For a deeper understanding, the pie chart in the lower right corner of Fig. 3 shows the share of constituents towards this GWP from Material. It can be seen that silver metal contributed overwhelmingly (92.95%) to GWP, followed by mercury (5.39%) and tin (1.66%). Additional material constituents include copper, zinc, etc., but their impacts were negligible as compared to the others and as such weren't included in the pie chart.

The bar chart in Fig. 6 shows the relative contribution of sources for the environmental impact of RBCs. It is important to mention that since the composite and the adhesive are used together in a single dental restoration, their impacts have been presented together. For this DRM, energy consumption (heat + electricity) for Material Processing and Packaging Processing had the greatest relative impacts across most of the LCIA categories. The third largest contributor across most of the categories came from materials used for Packaging (including syringe and compule for the composite/

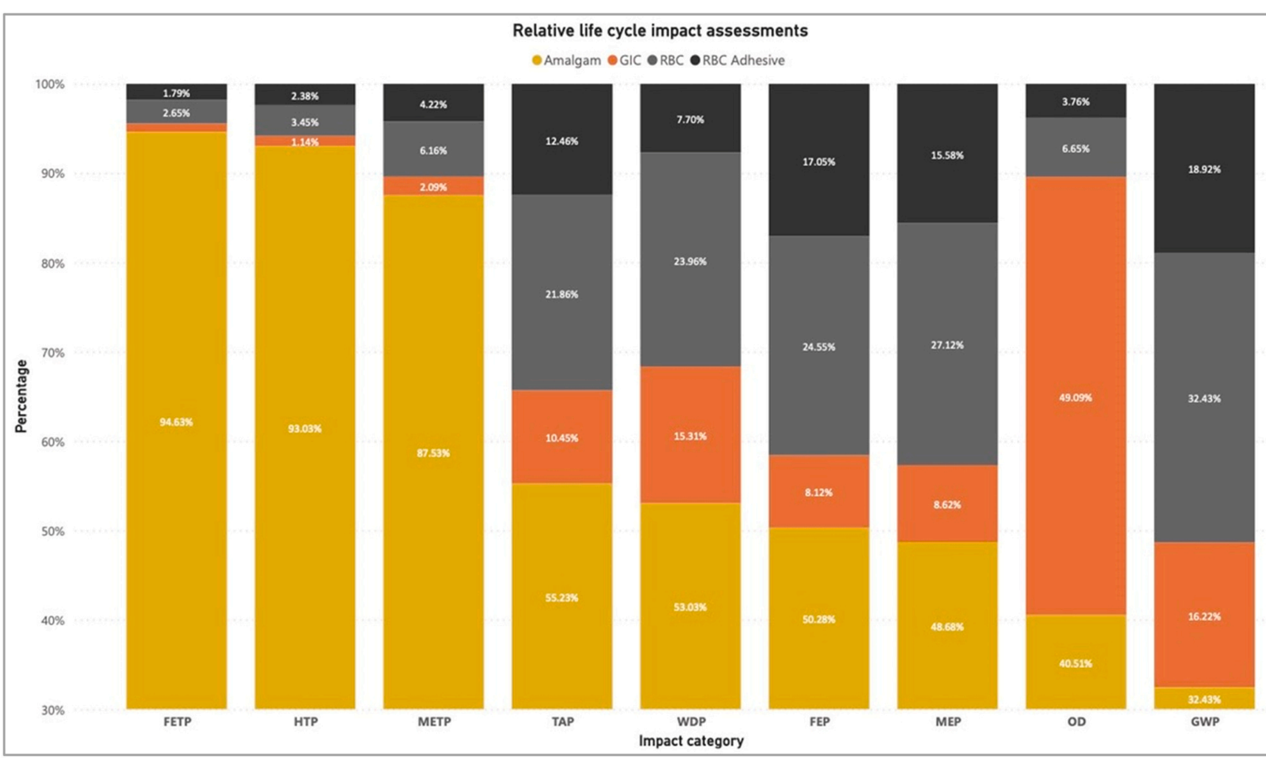

Fig. 4 – Comparison of LCIA categories for the DRMs.

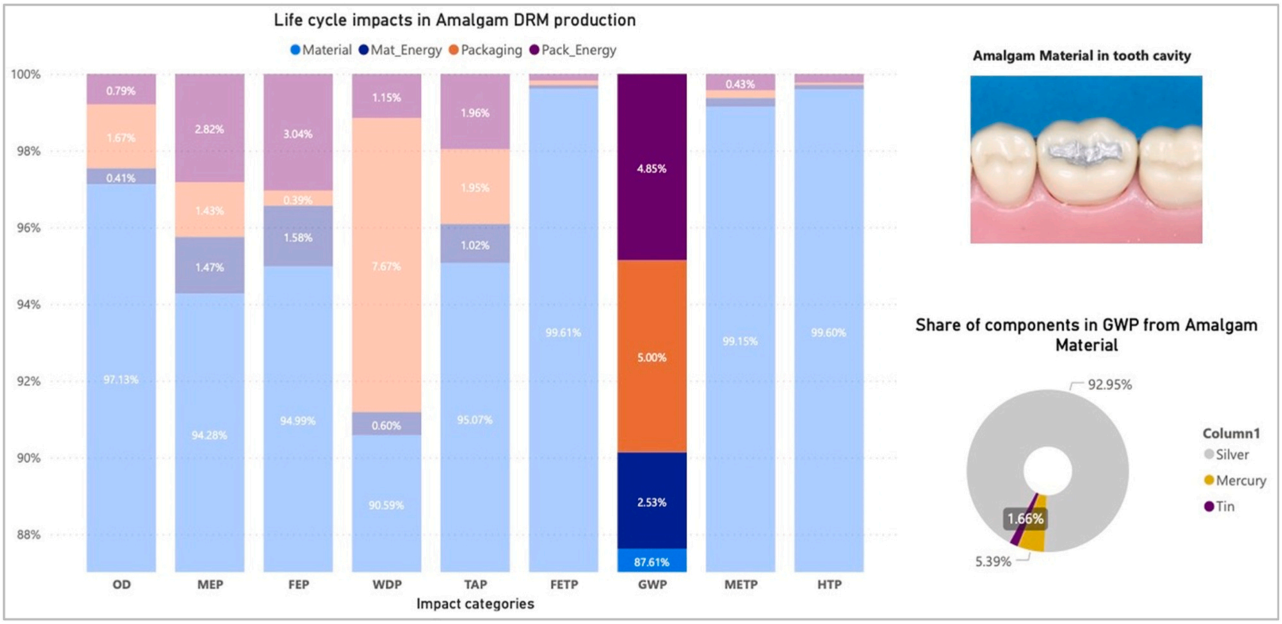

Fig. 5 – The percentage contribution of each component required in the production of one Amalgam restoration for each environmental impact category studied. Y-axis starts at 80% and GWP results are highlighted.

RBC and additional packaging for the Adhesive). The least impacts came from Material Processing.

In Fig. 6, the bar for GWP is highlighted for further elaboration of the results and shows that the greatest share of impact came from energy use in Packaging Processing (57.06%), followed by that from energy use in Material Processing (29.64%), followed by those from components used in producing different Packaging for the DRM (12.79%).

The impacts of different sources have been further disaggregated in the pie charts on the right-hand side of the

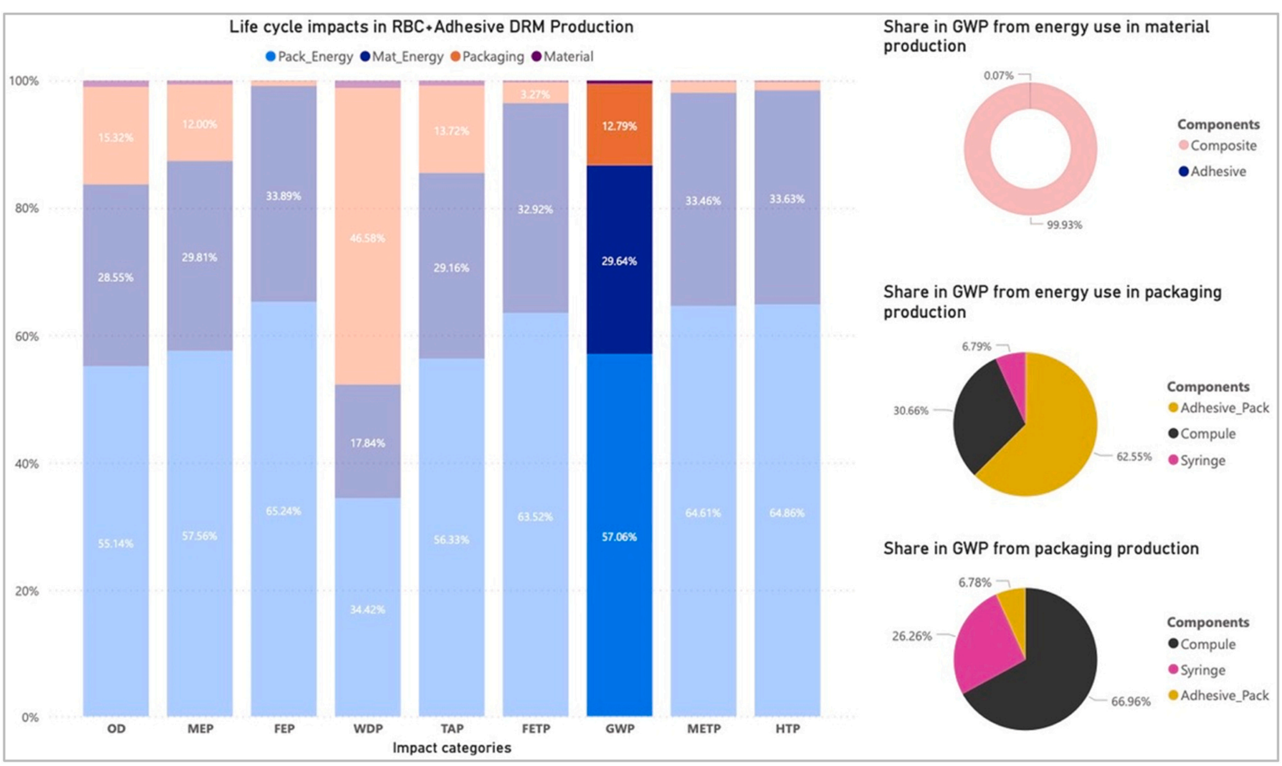

Fig. 6 – The percentage contribution of each component required in the production of one RBC restoration for each environmental impact category studied. GWP results are highlighted.

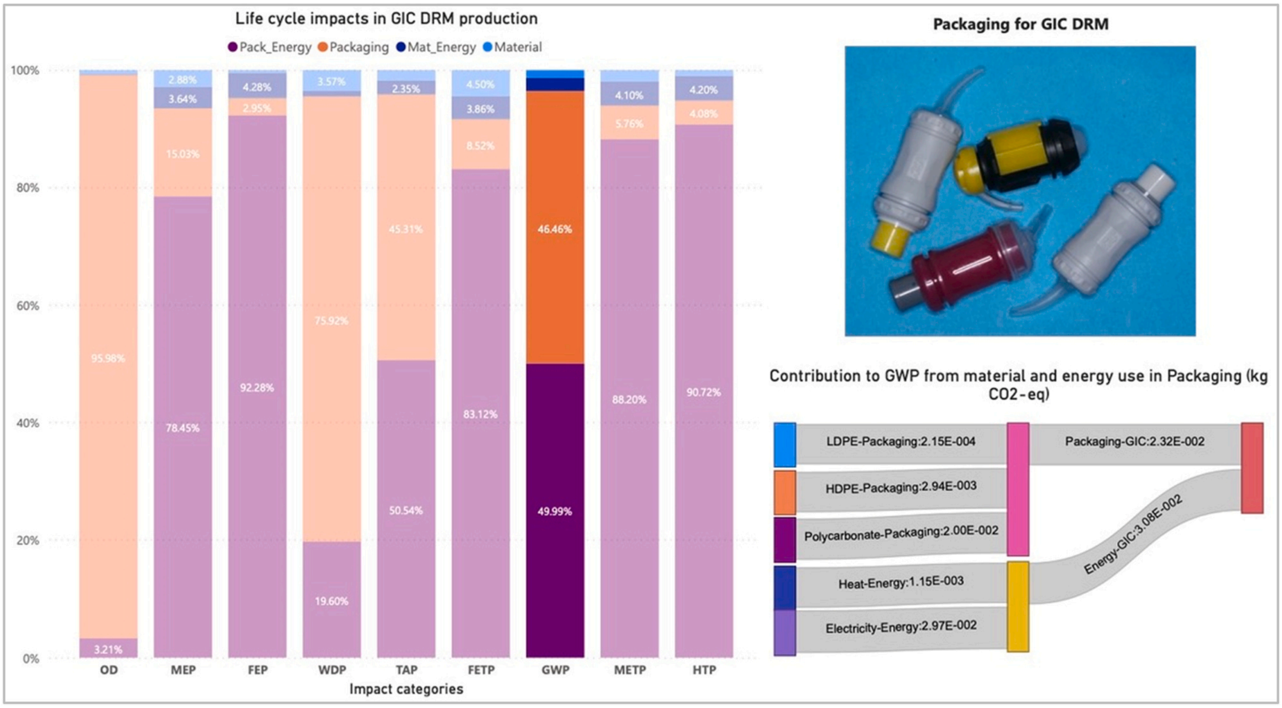

Fig. 7 – The percentage contribution of each component required in the production of one GIC restoration for each environmental impact category studied. GWP results are highlighted.

figure. The pie chart in the top-right corner shows the contribution of energy use in processing the materials towards GWP. It shows that the composite had an overwhelming share (99.93%) in the corresponding GWP impact. The remaining two pie charts display share in GWP from material and energy consumption in producing the packaging. For materials, those used in compule production resulted in the greatest share of GWP (66.96%) among all components. Conversely, for energy consumption in processing packaging, the share of energy used to process Adhesive packaging resulted in the highest GWP (62.55%).

These results can be further disaggregated in terms of the individual component flows in producing compule, syringe and adhesive packaging. However, this has not been discussed as the focus is on energy consumption which was the largest contributor of GWP for RBCs. This energy consumption included both grid electricity and heat use. This heat was also produced from electricity.

The bar chart in Fig. 7 shows the relative contribution of the four sources for life cycle impacts of GIC DRM production. Packaging and the associated energy consumption for Packaging Processing were the major contributors for all impact categories. The third largest contributor across most of the categories was Material whereas energy consumed in Material Processing had the lower impact for the majority of impact categories. The bar for GWP has been highlighted to display the share of different sources. It can be seen that most of the contribution to GWP came from energy (49.99%) and material (46.46%) used in packaging production.

The Sankey diagram in the lower right corner shows the contributions of the material and energy constituents to the GWP associated with Packaging Processing for GIC DRM. For material, polycarbonates had relatively the largest share of GWP impact (86.20%) whereas electricity use contributed the highest GWP from energy use in packaging production. Once again, the source of heat was also grid electricity and the energy sources have only been presented separately for illustrative purposes. A picture of the GIC primary packaging is displayed in the top right corner of Fig. 7.

4. Discussion

There is a research gap with respect to the application of LCA to determine the environmental impacts of dental restorative materials. Notwithstanding, the results of this study can be compared to a small number of available works.

The Centre for Sustainable Healthcare report, commissioned by Public Health England - PHE [24], reported that a dental amalgam restoration has a carbon footprint of 14.8 kg CO_2-eq, while this study reports the GWP of dental amalgam as 1.25E-01 kg CO_2-eq. Similarly, this study reports a much lower impact for both a RBC (1.20E-01 kg CO_2-eq, compared to 14.75 kg CO_2-eq reported by PHE), and a GIC (5.94E-02 kg CO_2-eq, compared to 8.6 kg CO_2-eq reported by PHE). The key difference between these two studies is the system boundaries applied. The PHE study concerns the application of these materials into a patient, included patient travel, staff travel, procurement, energy, water, waste and nitrous oxide, the study does not consider the production of the DRMs required for each of these restorative procedures. Therefore, as the system boundary of the present study concerns the environmental impact of the raw materials required for the manufacture of dental amalgam, RBC, and GIC restorative materials, it may be sensible to consider these results as complimentary and summate them to provide a cradle to grave system boundary.

4.1. *Environmental impact of the material architectures of the DRM systems*

Fig. 3 shows that across the majority of the environmental impact factors, the incorporation of silver into the dental amalgam has the highest environmental impact, (> 80%). Despite having the highest weight percentage of the material inputs to the dental amalgam (47%), mercury only shows the second highest impact. Mercury is a known environmental pollutant with associated negative health impacts when toxic thresholds are surpassed. When present within dental amalgam, there is no evidence that the mercury within this material causes serious harm, rarely local adverse events such as allergic reactions have been recorded [35]. However, the release of this material into the environment throughout its life cycle is the reason for its advised reduction and curtailment under the auspices of the Minamata Convention ratification. Other elements within dental amalgam also have potential negative environmental impacts, for example, the impact of released silver into the environment varies depending on its form [36] however it is known to be toxic to terrestrial and aquatic organisms [37].

From the dentist's surgery, the precious metals used in the production of amalgam find their way into the environment via numerous mechanisms [5] with global regional variations. Amalgam capsules are treated as hazardous waste and are mostly sent for incineration which results in the formation of incinerator ash. This ash, which contains traces of the dental amalgam, is then sent to landfill. Capsules could also be sent straight to landfill if they are unintentionally disposed of into municipal waste. In the dental surgery, dental amalgam debris is filtered via separators to reduce the volume of waste deposited in the water system. The combined effect of dental amalgam separators and purifying plants is calculated to remove 99% of mercury in wastewater before release into the natural environment [38]. Another pathway to the environment is via human waste excretion [39]. Overall, while the environmental impact of mercury in dental amalgam fillings cannot be ignored, it is clear that when a wider scope is applied to the other constituents of dental amalgam, the use and consequences of the silver content of this DRM must also be considered.

While RBCs and GICs contain different materials, their mobility through the environment mirrors that of dental amalgam. The environmental release of the monomeric components of RBC has potential negative impacts based upon their proven in vitro cytotoxic and genotoxic effects [40–42] and the release of bisphenol A (BPA) a known xenoestrogen [43]. The release of RBC waste in the form of

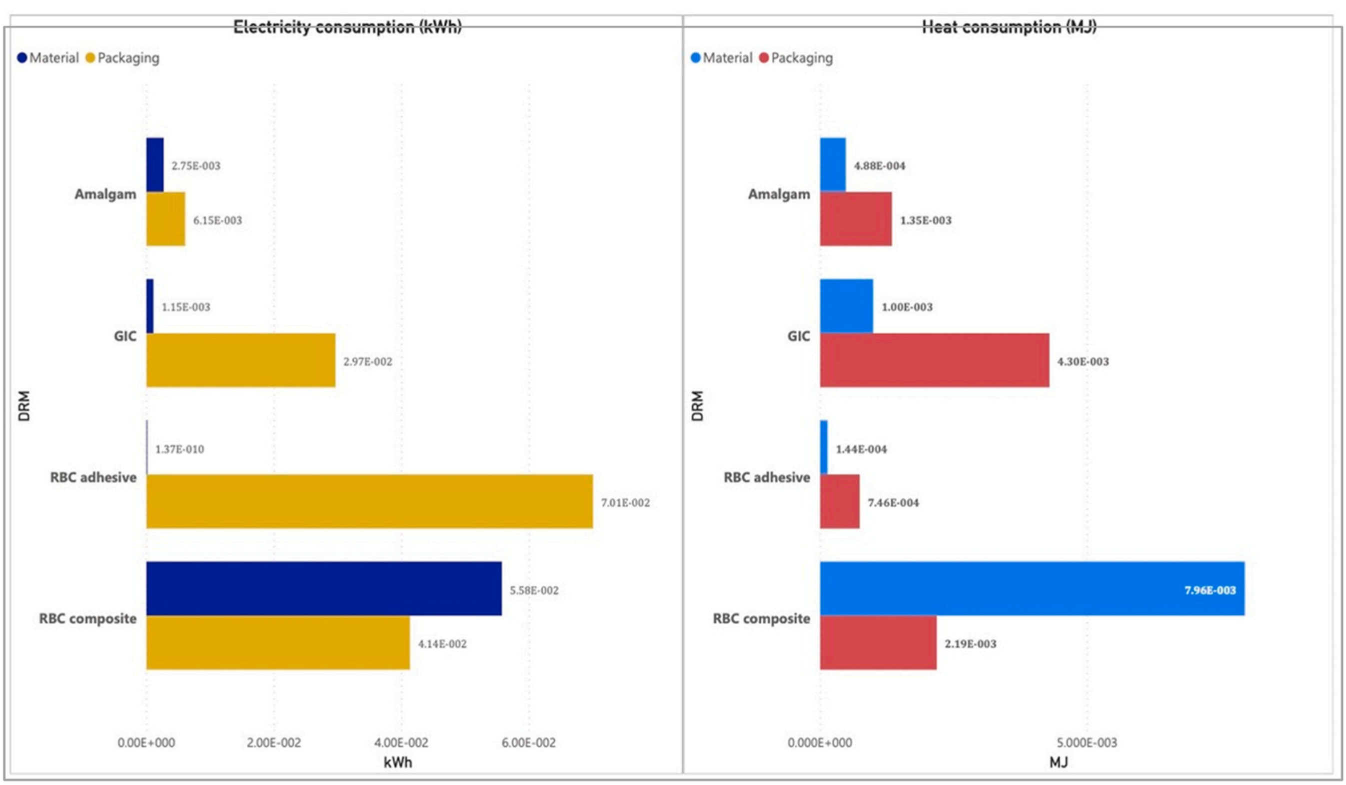

Fig. 8 – Electricity and heat use in material and packaging production for the DRMs.

microparticles generated through normal clinical use (such as removing an old restoration) further compounds these impacts due to the large surface area that these pollutants can elute [4,14,44].

The results provided in Fig. 6 show that a significant share of the environmental impact of RBCs is mainly caused by energy use. The use of material contributes significantly to some impacts only e.g., WDP. Most of this can be traced to resin and mineral filler in the material structure. Moreover, acetone and sulphuric acid in particular are significant contributors to environmental impacts [45]. Mineral fillers are produced on an industrial scale and the LCA results of compounds such as strontium bromide and sodium carbonate (or soda ash) for which carbonation, filtration and ammonia recovery process steps are required, demonstrate high environmental impacts from their production [46,47]. While the use of organic resin and solvent in the RBC adhesive structure led to a high contribution to a number of the environmental impact categories.

Similarly, to the RBC, the environmental impact of materials used in GICs is mainly spread across the use of mineral fillers. Other aspects that can influence the environmental impacts of mineral fillers include the high electricity requirements during manufacturing leading to increased results for the human toxicity environmental impact category [48].

With a steady reduction in the use of amalgam restorations, it is clear from a material input, that the alternative GIC materials provide a solution that has a reduced impact on the environment. Taken alone, the material inputs into the RBC restoration led to the lowest environmental impact, and remain similar when the impacts of the adhesive required to adhere the RBC to the tooth is also assessed.

4.2. *Environmental impact of the manufacturing energy requirements of the DRM systems*

To avoid the disclosure of proprietary company data, the individual process steps required for the manufacture of each DRM have not been provided. Fig. 8 presents the energy (electricity + heat) intake by source for manufacturing materials as well as packaging for each of the DRMs. It can be seen that a significant amount of energy is used in packaging for GIC and RBC DRMs which could perhaps be redesigned for efficiency gains.

This study uses the electricity mix (the national electricity board), medium voltage [kWh] dataset from Ecoinvent to provide an average impact for the electricity and heat use in DRM production [49]. A reduction in the total impact of the electrical energy required in the production of each DRM could be achieved through decarbonisation. Decarbonisation of the national grid which can be accomplished through the implementation of renewable energy resources, nuclear power generation or an increase in the utilisation of gas, for example. The same end can also be achieved through a reduction in demand that equates to energy efficiency savings [50,51]. A reduction in thermal energy requirements can be achieved through efficiency savings such as the implementation of sensors and controls, the use of appropriate refractory materials to reduce heat loss, ensuring efficiency heat transfer within furnaces and the recovery of heat to reuse in other processes [52].

4.3. *Environmental impact of the packaging requirements of the DRM systems*

Fig. 6 shows that the packaging requirements for the GIC DRM has the highest impact caused by the packaging materials; the use of polycarbonate (PC) in this packaging (47 wt%) results in majority of the GWP impact. The GWP of the dental amalgam packing has the highest percentage contribution from the use of low-density polyethylene (LDPE) and the use of polyamide-6 leads to the highest percentage contribution of the GWP for the RBC packaging. The GIC DRM packaging would benefit, where possible, from substituting PC for a polyolefin polymer such as LDPE, PP or high-density PE. As PC production involves addition chemical processing between the oil refinery and polymerisation, it has a higher environmental impact than polyolefin polymers and therefore making this substitution would reduce the environmental impact of this packaging type [53].

As shown in previous studies, developing strategies to recycle medical waste will not only reduce the environmental impacts of utilising virgin materials during the manufacturing process, it will also reduce the costs of waste disposal and reduce the burden of waste polymers on landfills [54,55].

The component level analysis presented in Figs. 5 through 7 can be helpful in process improvements as indicated in the framework provided in Fig. 1. For instance, replacement of silver and mercury with suitable alternatives can reduce the life cycle impacts and potentially make dental amalgam a suitable choice. Similarly, by changing energy sources for RBC manufacturing, the resulting impacts can be lowered significantly. The impacts for GIC can be reduced by redesigning packaging to include alternatives to polycarbonates. Once these changes have been made, another LCA can be conducted to compare the three DRMs. These results can be combined with other criteria such as economic and social elements to choose the best alternative.

5. Conclusions

This study compared the relative life cycle impacts from three direct-placement dental restorative materials (dental amalgam, RBC and GIC), using primary data from the manufacturer. The study considers the material and associated packaging of the individual DRMs and it includes a comparison of energy consumption in processing the materials for final output. The study shows empirically that dental amalgam generally has the highest life cycle impacts across most of the categories. GIC has relatively the lowest impact across the corresponding categories. These impacts could be reduced further through efficiency gains in packaging design. For RBC to be better positioned as a suitable dental amalgam alternative, less intense energy sources should be explored and analysed. The longevity and need for replacement (with associated environmental impacts) of the restorations discussed in this research has not been discussed and would form the basis of future work to elucidate the optimal material in a true cradle-to-grave study.

This study includes the introduction of a closed loop integrated framework that delineates steps for continuous process improvements through a combination of primary data, LCA and root cause analysis. The framework proposes that the LCA results for DRMs can help identify the processes and material inputs with the greatest environmental impacts. Corrective action can include a combination of changes in energy, manufacturing and material choices. These changes will be reflected in another LCA until the margin for improvement becomes insignificant.

The limitations of this study are the use of environmental criterion only to identify the optimal DRM and financial and clinical durability indicators could be used for a more holistic assessment. In addition, the use of other energy sources could have relatively lower environmental impacts. A future study could consider the use of more sustainable and renewable energy sources for impact assessments. The comparison of data from different manufacturers to identify best practices is desirable but competitive practice makes this unattainable. While this study provides three self-contained case studies, the results will have a wider impact than dentistry alone with respect to the use of single-use plastic packaging within the healthcare system.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.dental.2022.11.007.

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